Renewable and Sustainable Energy Reviews 15 (2011) 3658–3668

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Quantification of provincial-level carbon emissions from energy consumption in China

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ARTICLE INFO

Article history:
Received 14 December 2010
Received in revised form 13 April 2011
Accepted 5 July 2011
Available online 6 August 2011

Keywords:
Carbon intensity
Economic development
Per capita emission
Fuel types
Distribution

ABSTRACT

Greenhouse gas emission inventories are useful tools for monitoring air quality and assisting local policy development. This article estimates CO_2 emission inventories from energy consumption and carbon intensities of provinces and municipalities in Mainland China in 1990, 1995, 2000, and 2005–2008 using the IPCC mass balance approach. Results show that China's coal-based energy structure and unique economic development have heavily impacted CO_2 emissions. Fortunately, although coal consumption has increased to over 70% of all fuel use, the share of CO_2 emissions from coal has gradually decreased due to energy consumption restructuring. The switch from coal-dominance to cleaner, renewable energies (wind, solar, natural gas, nuclear power, geothermal, biomass energy) will undoubtedly reduce CO_2 emissions in China. Results also indicate that carbon intensity has improved steadily, as China's economic development introduces new technologies intended to minimize environmental pollution and destruction. Our results suggest that China's CO_2 emissions may not be as high as expected in future, and will gradually lessen.

Contents

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doi:10.1016/j.rser.2011.07.005

1. Introduction

The planet's most prominent developing country, China has undergone rapid economic development, with an average annual Gross Domestic Product (GDP) growth rate exceeding 10%. In 2008 China was the third largest economy in the world, just behind the United States and Japan, with a nominal GDP of 4.43 trillion US dollars [1]. As a result, energy consumption in China has increased rapidly, accompanied by energy-related CO_2 emissions, one of the main greenhouse gases. In 2005 CO_2 emissions in China were still 2% below those of the United States, but in 2006 China surpassed America by 8% to become the number one CO_2 emitter [2,3]. Reducing CO_2 emissions is not only key to China's sustainable development; it is also an urgent international concern.

In recent years, the Chinese government as well as domestic and foreign scientists has increasingly focused on CO_2 emissions produced by energy consumption and economic activities in China. Dhakal [4] measured urban carbon emissions in China and investigated the contribution of energy usage. Li et al. [5] examined energy demand and carbon emissions under different development scenarios in Shanghai. He et al. [6] identified the main characteristics of CO_2 emissions from fossil energy combustion in China and estimated future emissions. Zhang et al. [7] applied the TY procedure to test long-term Granger causality and used impulse response analysis to investigate the relationships among GDP, energy consumption, and carbon emissions in China. Bing et al. [8] reported on China's energy development strategies under a low-carbon economy. Hwang et al. [9] gave a policy review on the GHG emissions reduction in Taiwan. These authors all calculated the CO_2 emissions of China's several mage-cities and examined the relationship between energy consumption and economic growth. Besides, among western country, researches are very active. Ali and Ilhan [10,11] examined the causal relationship between carbon emissions, energy consumption, and economic growth by using autoregressive distributed lag in Europe. Kamil [12] discussed the energy and environmental issues relating to GHG emissions for sustainable development in Turkey. However, there is very little discussion on the combined issues of energy structure, population, geological distribution, and economic growth with respect to large-scale CO_2 emission. To date, China's overall CO_2 emission from energy consumption has not been estimated for purposes of developing and improving policies and strategies for the future.

To effectively control and reduce CO_2 emissions from energy consumption in China, it is important to know the history and current status of its CO_2 emissions. Although different inventory methods have been used, including actual measurement, emission coefficient estimates, and the mass balance method, there is no standard or optimal way to calculate an emission inventory [13–15]. The main objectives of this paper are (1) to estimate CO_2 emissions from fuel consumption in provinces and municipalities in Mainland China in 1990, 1995, 2000, and 2005–2008; (2) to analyze the relationships among geological distribution, population, economic development, energy structure, and CO_2 emissions; and (3) to propose long-term carbon reduction strategies for decision makers.

2. Study areas, methodology, and data

2.1. Study areas

In all, China contains 23 provinces, 4 municipalities, 5 autonomous regions, and 2 special administrative regions. This study covers only 22 provinces, five autonomous regions, and four municipalities. Data for Xizang Province were unavailable. The four municipalities Beijing, Shanghai, Tianjin, and Chongqing were selected because they have seen the highest rate of economical development in China since 1978. They are also the most important political, economic, and cultural centers, with populations of over 10 million. Beijing, Shanghai, and Tianjin have been municipalities for many decades and are highly urbanized, whereas Chongqing was a part of Sichuan Province until early 1997 and is now the largest municipal government, although located far inland in a less developed area [4]. Mainland China can be divided into seven major divisions according to geographical zone and economic development: Northern China, Northeast China, Eastern China, Central China, Southern China, Southwest China, and Northwest China. Fig. 1 shows a map of China with its municipalities, provinces, and geographic divisions.

2.2. Methodology

We use a mass balance approach to estimate CO_2 emissions from energy consumption in China. Thus, a quantitative analysis is applied to evaluate the resource materials used in industrial processes such as industrial production, manufacturing, processing, power supply, heating, and transport, based on the Law of Conservation of Mass. Following IPCC guidelines, CO_2 emissions from energy consumption are calculated using Eq. (1), as follows [5,16]:

$$E_{CO_2} = \sum_i \sum_j \frac{Aij \times \mathrm{NCV} \times Cij \times Oij \times 44}{12} \quad (1)$$

where E_{CO_2} is the total CO_2 emission from energy consumption (ton); Aij is the amount of fuel consumption j in sector i (tons or million m^3 for natural gas); NCV is the net calorific value (kJ/(kcal × kg)); Cij is the carbon emission factor of fuel j in sector i (kg/GJ); and Oij is the carbon oxidation rate of fuel j in sector i. The fuels considered in this paper include the fuel categories used in energy balance tables: raw coal, coke, crude oil, fuel oil, gasoline, kerosene, diesel, and natural gas [5,16].

2.3. Data sources

Energy consumption data for each region in 1990, 1995, 2000, and 2005–2008 are obtained from the *China Energy Statistic Yearbook* [17]. Because Chongqing was founded in 1997, data for Chongqing are available for after 1997 only. The net calorific values for each fuel are also obtained from the *China Energy Statistic Yearbook* [17] (Table 1) and carbon emission factors are selected from the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (Table 1). Annual GDP data and resident populations are obtained from the 1991, 1996, 2001, and 2006–2009 *China Statistics Yearbook*. Energy statistics for the earlier years are available at 5-year



Fig. 1. Distribution of the municipalities and provinces in China.

intervals from 1990 to 2000 and available thereafter for each year from 2005 to 2008. The carbon oxidation rate for the different fuels (O) is taken as the default value of 1, according to the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories.*

3. Results

3.1. CO_2 emission inventories in China

Using the mass balance approach and fuel consumption statistics [17], China's mainland provincial level CO_2 emissions inventories for 1990, 1995, 2000, 2005–2008 are estimated and reported in Fig. 2 and Appendix A.

In general, the total CO_2 emission in China has increased steadily over the past two decades, from 5638.25 Mt in 1990 to 19283.31 Mt in 2008, for an average annual growth rate of 7%. Similarly, the total CO_2 emission of individual provinces also increased steadily from 1990 to 2008. However, CO_2 emissions were noticeably unequal across provinces. Regional CO_2 emissions decreased from north to south and from east to west. From 2005 to 2008, CO_2 emissions consistently exceeded 400 Mt in four provinces: Hebei, Shanxi, Jiangsu, and Shandong. Located in the northeast, these are traditional industry-based or economically intensive regions. Conversely, CO_2 emissions in Jiangxi, Hainan, Qinghai, and Ningxia were considerably lower. CO_2 emissions also increased significantly in Shandong from 2005 to 2008, with total CO_2 emissions reaching 1933.04 Mt in 2008. In Hebei, Shanxi, and Shandong, CO_2 emissions increased over 1990 levels by 1050.36 Mt, 1004.87 Mt, and 1530.75 Mt, respectively. In the other provinces, CO_2 emissions increased by less than 1000 Mt, with a notable increase of less than 100 Mt for Qinghai. Interestingly, although 2008 CO_2 emissions in Hainan were over 30 times higher than in 1990, Hainan currently has the lowest emission among cities where tourism is a pillar industry.

In terms of region, Eastern China contributed the largest portion of CO_2 emissions (Fig. 3), at about 4200–5500 Mt from 2005 to 2008, or approximately 30% of China's overall emission. The next three largest contributors were Northern, Northeast, and Central China, accounting for 10–20%, respectively. This was mainly due to their far denser populations and advanced industrialization. CO_2 emissions in Southern, Southwest, and Northwest China were significantly lower than in the other regions. Interestingly, Eastern, Northern, Northeast, and Central China cover about 45% of the mainland and accounted for over 75% of China's CO_2 emission, whereas the other three regions cover approximately 55% of the territory but accounted for less than 25% of the overall CO_2 emission.

Of the four municipalities, Shanghai had the highest CO_2 emission (Fig. 4). From 2005 to 2008, Shanghai held the lead as the largest CO_2 emitter. In 2008 CO_2 emissions in Shanghai reached 451.96 MT, whereas CO_2 emissions in Beijing, Tianjin, and Chongqing were 252.38 MT, 274.46 MT, and 279.90 MT,

Table 1
Net calorific value of fuels (NCV) and the default carbon emission factor (C).

Energy	Net calorific value[a]	Default carbon emission factor (kg/GJ)[b]
Raw coal	20,908 kJ/(5000 kcal)/kg	26.8
Coke	28,435 kJ/(6800 kcal)/kg	22.0
Crude oil	41,816 kJ/(10,000 kcal)/kg	20.0
Fuel oil	41,816 kJ/(10,000 kcal)/kg	21.1
Gasoline	43,070 kJ/(10,300 kcal)/kg	20.2
Kerosene	43,070 kJ/(10,300 kcal)/kg	19.6
Diesel	42,652 kJ/(10,200 kcal)/kg	20.0
Natural gas	38,931 kJ/(9310 kcal)/m^3	15.3
Electricity	3596 kJ/(860 kcal)/kW h	0.5772–0.7802[c]

[a] 2009 China Energy Statistic Yearbook.
[b] 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
[c] CO_2 emission factor obtained from the National Development and Reform Commission, 2009.

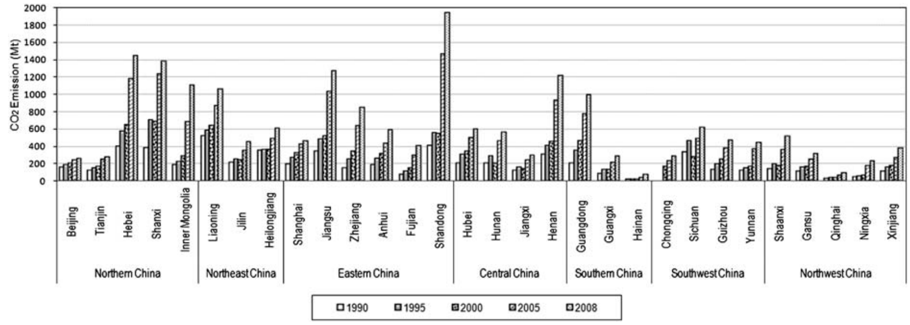


Fig. 2. Chinas provincial annual total CO_2 emissions.

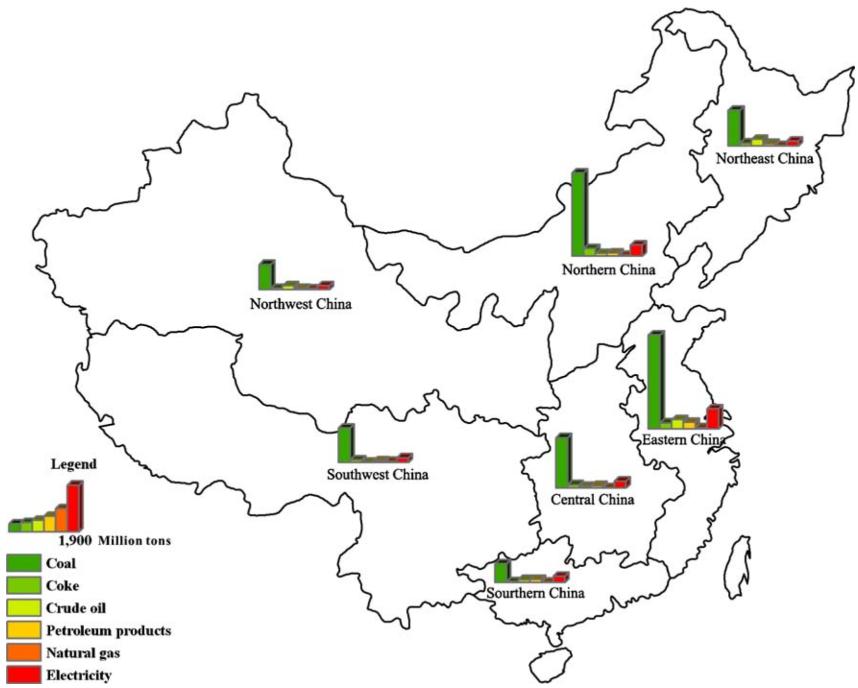


Fig. 3. Chinas regional CO_2 emissions in 2008.

respectively. Furthermore, clear differences are seen in the temporal change in CO_2 emission inventories over the last two decades. For instance, Fig. 4 shows that CO_2 emissions increased more slowly over time in Beijing and Chongqing than in Shanghai and Tianjin. CO_2 emissions increased by 64.39% and 78.41% in Beijing and Chongqing versus 145.91% and 137.04% in Tianjin and Shanghai. This was because Shanghai and Tianjin already contained a large number of industrial plants and recently introduced many new ones.

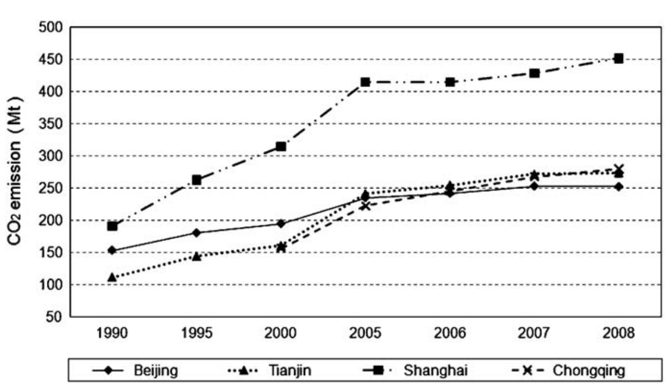


Fig. 4. Four municipalities CO_2 emissions from 1990 to 2008.

3.2. CO_2 emissions by fuel type

According to the CO_2 emission inventories by fuel type (Fig. 5), coal combustion was clearly the leading contributor to the total CO_2 emission, as coal has dominated China's energy consumption mix. However, from 2005 to 2008, coal consumption accounted for less than 50% of the total energy consumption, even though coal combustion emitted about 50 billion tons of CO_2, contributing over 70% of the national gross CO_2 emission. Note that although the total amount of CO_2 emissions from coal use increased by about 9400 Mt in the last 20 years, the share of the total CO_2 emission from coal dropped from 76.91% in 1990 to 71.34% in 2008 due to energy restructuring.

The second contributor of CO_2 emissions was electricity consumption, at about 10% of the total emission. Due to its central role in the energy structure, electricity CO_2 emissions increased from 419.85 Mt in 1990 to 2334.83 Mt in 2008, accounting for 7.45% and 12.11%, respectively. At the same time, electricity consumption increased from 15.27% of the total energy use in 1990 to 23.36% in 2008. Therefore, electricity is relatively cleaner than

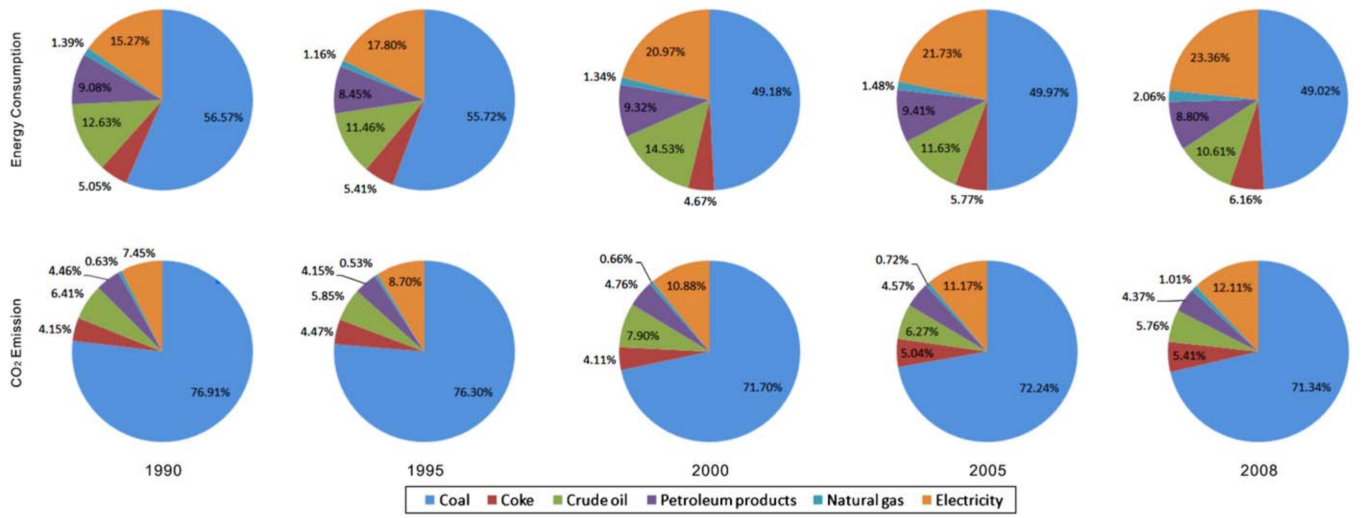


Fig. 5. National annual energy consumptions and CO_2 emissions by fuel types.

coal. This emission share was unavoidable, but could be reduced through energy-saving measures.

Coke and crude oil combined contributed about 10% of the total CO_2 emission. These two industrial raw materials showed different CO_2 emission and energy consumption trends. The shares for coke increased while shares for crude oil decreased. These trends were affected mainly by market price adjustments.

The share of CO_2 emissions from petroleum products increased steadily from 4.25% in 2006 to 4.37% in 2008, whereas consumption shares decreased from 9.10% in 2006 to 8.80% in 2008. Petroleum products (including fuel oil, gasoline, kerosene, and diesel) are used mainly in transport and commerce. The increasing demand for ground transportation fuel was the major cause of petroleum consumption. CO_2 emissions from ground transportation were also high. In the long term, transport energy is expected to rise with increasing urbanization. Some promising solutions to reduce petroleum consumption include developing hybrids or electric vehicles and promoting low-displacement vehicles.

3.3. *Distribution of CO_2 emissions by GDP and per capita*

Generally speaking, economic development and population expansion have produced increasing CO_2 emissions. In this study, CO_2 intensity and CO_2 emissions per capita are calculated as key indicators of the extent to which the economy and population depend on energy. CO_2 intensity is defined as the amount of CO_2 emissions per GDP produced. Lower CO_2 intensity means that more low-carbon technologies can support higher economic activity [18]. Figs. 6 and 7, Appendix B and C present the historical CO_2 intensity and CO_2 emissions per capita for the municipalities and provinces.

3.3.1. *Variation in CO_2 intensity*

No significant differences in CO_2 intensity were observed across our study areas. The overall trend for each province decreased sharply before 2005 and declined slowly after 2005 (Fig. 6 and Appendix B). This differs from the trend in the total CO_2 emission for each province. This is attributable to the close relationship between CO_2 emissions and GDP in each province (R^2 = 0.7841–0.99876, $P < 0.05$) (Fig. 8). In other words, CO_2 emissions were proportionate to GDP. The overall trend toward lower CO_2 intensity resulted from the continuous replacement of high-carbon with low-carbon fuels.

Before 2008, Shanxi's CO_2 intensity was consistently the highest. It decreased from 8.55 kg/Yuan in 1990 to 2.49 kg/Yuan in 2007, followed by Ningxia's, which decreased from 6.53 kg/Yuan in 1990 to 2.35 kg/Yuan in 2007 (2009 average exchange rate, 1US$ = 6.832Yuan) (Fig. 6). For centuries, Shanxi was reputed as China's greatest coal producing province. However, instead of retaining large profits, it supplied coal to the other provinces. Therefore, although its GDP was not very high, it had the greatest coal consumption, and consequently the highest CO_2 intensity. Ningxia was also a major coal producing province, yet 45% of its coal was supplied to other areas. In addition, high-energy-consuming enterprises developed rapidly in Ningxia, generating higher CO_2 emissions and lower GDP. In 2008 Ningxia surpassed Shanxi's long-held lead and emitted 2.04 kg/Yuan. At the same time, each of the other provinces emitted less than 2 kg/Yuan. The effect of industrial energy restructuring was not apparent in Ningxia. In addition,

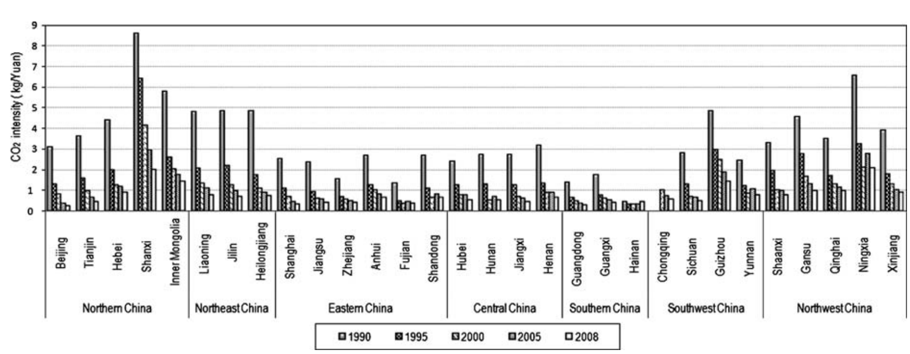


Fig. 6. Chinas provincial annual CO_2 intensity.

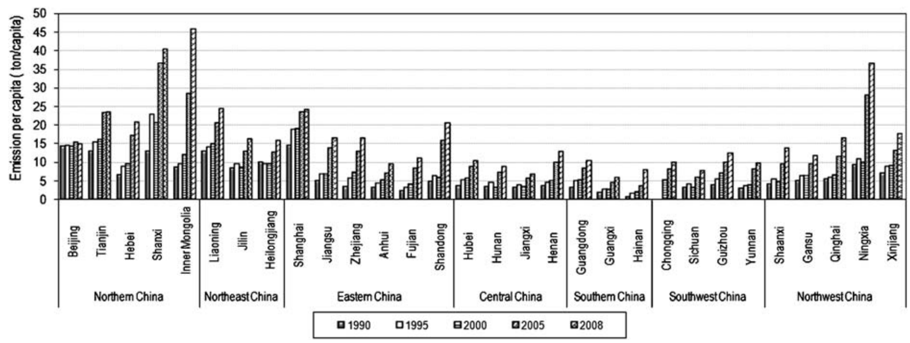


Fig. 7. Chinas provincial annual per capita CO_2 emissions.

Beijing's CO_2 intensity was the lowest since 2005, undoubtedly due to the "Green Olympics" approach in Beijing City.

We conducted further comparisons of CO_2 intensity and economic development (Fig. 9). From 2005 to 2008, taking a national annual CO_2 intensity of 0.59 and a GDP growth rate of 16.8% as the dividing line, the economic development of the provinces can be divided into three modes: high GDP/low CO_2 emission, mid-GDP/mid-CO_2 emission, and low GDP/high CO_2 emission. Fig. 10 illustrates the regional imbalance in economic development and emissions. The whole of Eastern and Southern China, except for Shandong and Anhui, are categorized as high economic development/low CO_2 emission, whereas the majority of Northwest, Northern, Southwest, and Northeast China, except for Jilin, Shaanxi, and Sichuan, are categorized as low economic development/high CO_2 emission. The remaining provinces are situated around the mean. Of the four municipalities, Beijing, Tianjin, and Shanghai show high economic development/low CO_2 emission. Overall, the coastal provinces in Southeast China developed much more efficiently than Central and Northwest China.

We also estimated the regional and national average mean CO_2 intensity in relation to energy consumption (Fig. 11). The national average CO_2 intensity decreased rapidly in the last decade, and has dropped steadily since then. It decreased by 22.4% from 2005 to 2008 and by 81.0% from 1990 to 2008. The intensity for Northern, Northeast, Southwest, and Northwest China was consistently above average, but below average for the other three regions. This agrees well with our above analysis. It is encouraging to see that CO_2 intensity for all the regions approaches the average with time.

Data were collected on Beijing, Shanghai, Tianjin, and Chongqing to determine urban CO_2 intensity. Fig. 12 shows that urban CO_2 intensity was consistently lower than average. This is because cities have a distinct advantage in terms of energy consumption. China's rapid urbanization is expected to foster further improvements in both energy consumption and economic growth.

3.3.2. CO_2 emissions per capita

Under the Chinese government's macro-control, CO_2 emissions per capita increased in the provinces, albeit slowly (Appendix C). Per capita CO_2 emissions in Inner Mongolia, Shanxi, and Ningxia continued to occupy the top three (Fig. 7), at 45.51 tons/capita, 40.23 tons/capita, and 34.23 tons/capita in 2008, respectively, far above the average of 14.52 tons/capita. The low points in Shanxi in 2000 and 2008 and in Inner Mongolia in 2007 were due to reductions in energy consumption. In the other provinces, CO_2 emissions per capita were efficiently controlled and grew slightly. However, the regional distribution showed an opposite trend: Eastern China had higher per capita CO_2 emissions than Central and Southern China.

Regional per capita CO_2 emissions are shown in Fig. 13. Northern and Northeast China's per capita CO_2 emissions far exceeded the national average, and the gap grew with time. As shown in Fig. 13, the substantially uneven development between the eastern and

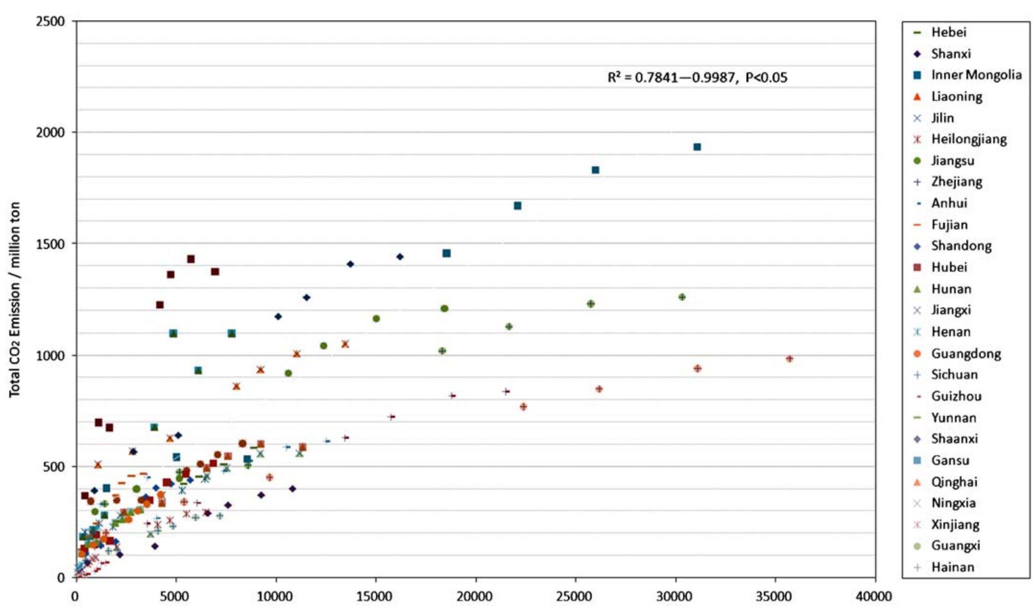


Fig. 8. Relationships between GDP and CO_2 emission of each province.

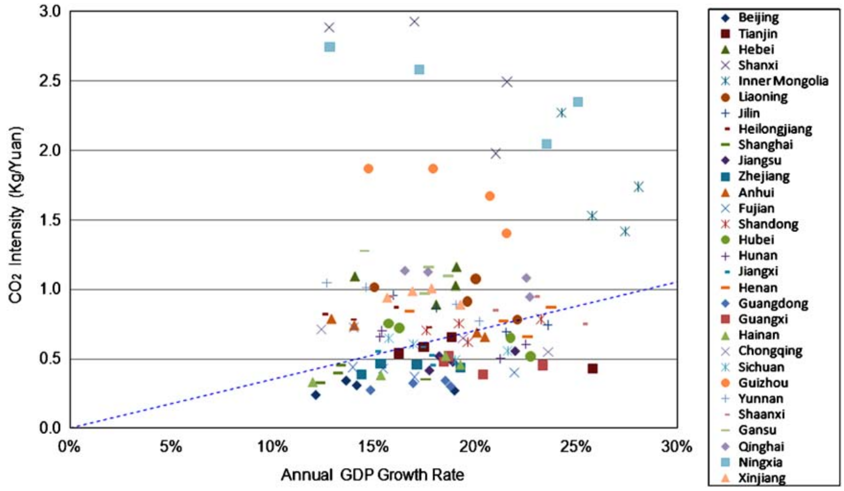


Fig. 9. Relationships between CO_2 intensity and annual GDP province.

western regions continued. The maximum disparity increased from 8.11 tons/capita in 1990 to 19.55 tons/capita in 2008. Concerted efforts should be made to narrow this gap.

Of the four municipalities, CO_2 emissions per capita for Beijing, Shanghai, and Tianjin were about 14 tons/capita each in 1990. However, these indicators had almost doubled in Shanghai and Tianjin by 2008, whereas they remained steady in Beijing (Fig. 14). This was because the Olympic Games provided a powerful motivation for environmental improvement in Beijing. Chongqing's CO_2 emissions per capita were much lower than the other three cities, increasing from 5.08 tons/capita in 2000 to 9.86 tons/capita in 2008. This was due to the large population in Chongqing: at over 28 million, it was almost twice the population of other municipalities. Therefore, it would be advisable to control Shanghai and Tianjin's CO_2 emissions per capita by adjusting the energy structure.

Urban and national average per capita CO_2 emissions are shown in Fig. 15. The national average increased from 5.00 tons/capita in 1990 to 14.77 tons/capita in 2008, which far exceeds the world average of 4.48 tons/capita in 2008, but is nevertheless lower than the USA's 19.78 tons/capita [19]. However, the urban per capita CO_2 emissions also remained far above average, even though regional gaps may be narrowing. Fortunately, urban per capita CO_2 emissions did not increase substantially, but remained steady. Even so, China has a long way to go before reaching the global average.



Fig. 10. Distributions of Provinces according to the Three Developing Modes.

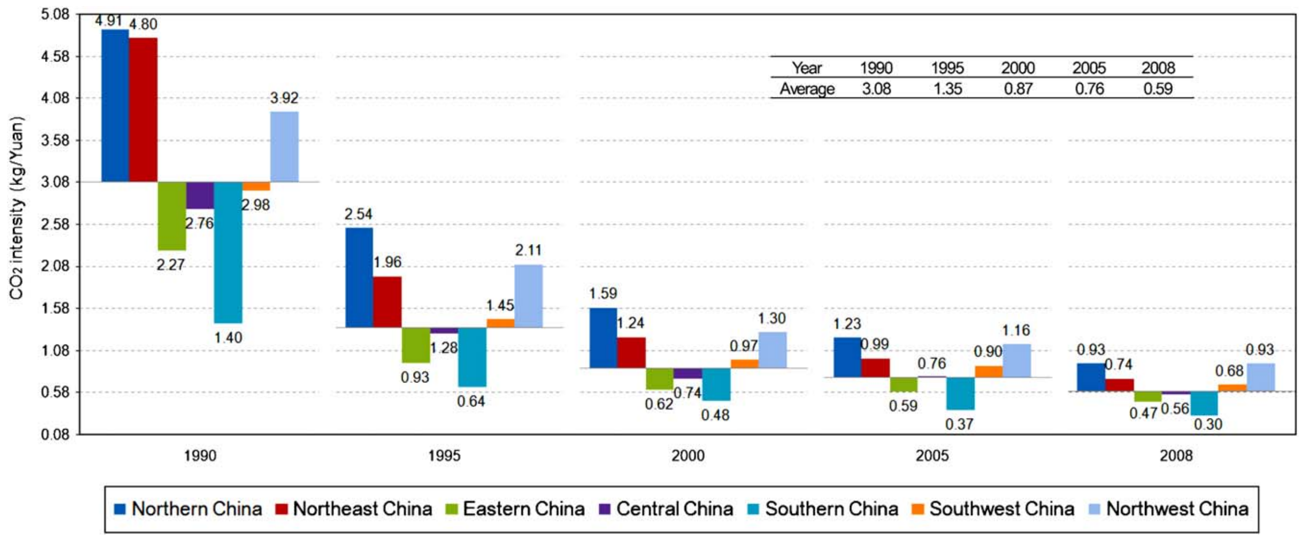


Fig. 11. Comparasion of regional CO_2 intensity and national.

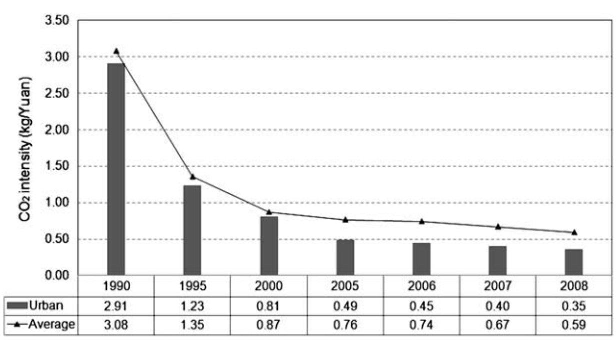


Fig. 12. Comparasion of urban CO_2 intensity and national.

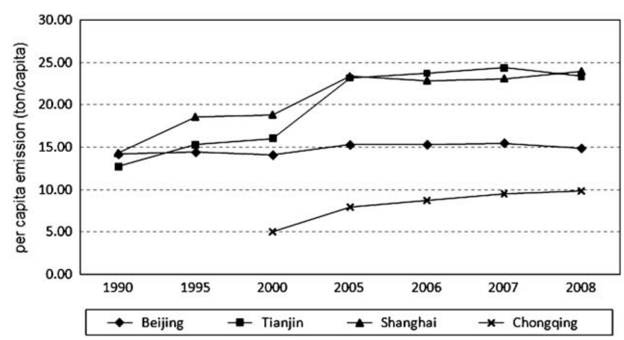


Fig. 14. Four municipalities per capita CO_2 emissions from 1990 to 2008.

4. Discussion

4.1. Relationships among the economy, energy use, population, and CO_2 emissions

Economic development, energy consumption, and population are all factors that influence CO_2 emissions in China (Fig. 16). As the biggest developing country, China has set its priority on developing its economy and eliminating poverty now and in future. Therefore, economic growth is the main factor driving the growth of energy consumption and CO_2 emissions. At present, although the use of clean energy is increasing, China's coal-dominated energy structure will persist for at least two decades, and will result in many more CO_2 emissions. Nevertheless, a total CO_2 emission inventory

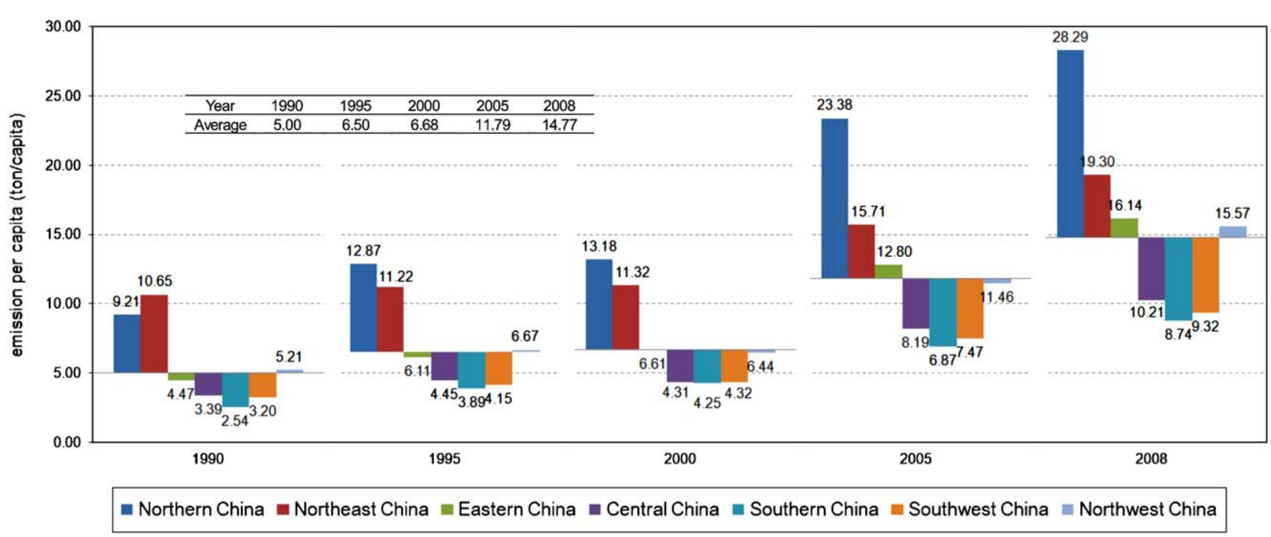


Fig. 13. Comparasion of regional per capita CO_2 emissions.

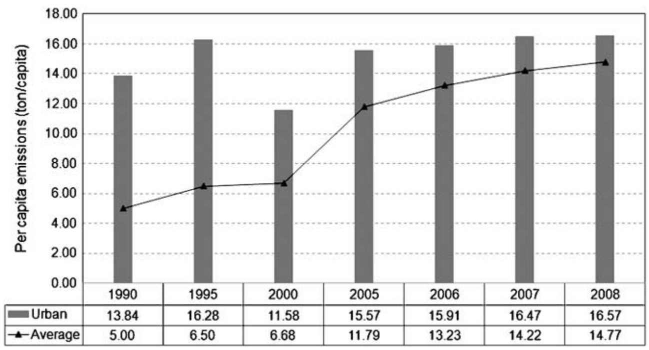


Fig. 15. Comparasion of urban per capita CO_2 emissions.

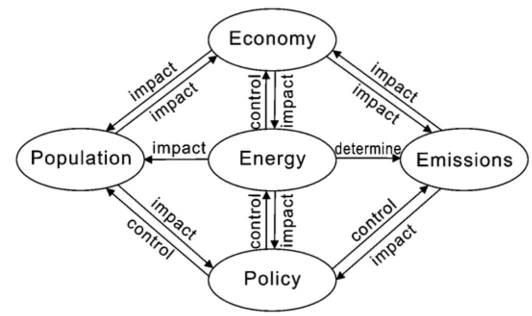


Fig. 16. Relationships among economy, population, energy use and emissions.

is not the only way to measure carbon emissions. Per GDP emissions and per capita emissions are more accurate for purposes of regional sustainable development. Therefore, GDP and population also play important roles in determining regional CO_2 emission capability. On the other hand, CO_2 emissions also place harsh constraints on Chinese economic development. Excessive emissions are associated with climatic deterioration, and ultimately they lead to disasters, all of which slow the national economy. Economic and environmental policies should be coordinated in order to enhance sustainable development of both the economy and society. This will necessitate a continuous, low-carbon energy supply [8].

4.2. Countrywide emissions analysis

The two types of CO_2 emissions from energy consumption are: (1) a coal-dominated energy mix, which contributes to most emissions, and (2) imbalanced CO_2 emissions between the East and the West. Fortunately, the share of CO_2 emissions from natural gas has been increasing in recent years. Although natural gas consumption grew by 68 billion cu.m from 1990 to 2008, its share of CO_2 emissions was only about 1%. This switch indicates that energy consumption restructuring in certain cities—from coal dominance to greater share of clean energy such as natural gas, hydropower, and solar—is effective to control CO_2 emissions. Moreover, with the implementation of large-scale development of the western region and programs to transfer electricity and natural gas from west to east in China, several large energy-based construction projects have been initiated in the southwest and northwest provinces [20,21]. This will greatly spur western China's economy and fossil energy consumption. CO_2 emissions are therefore expected to increase gradually in China's western regions.

4.3. Urban CO_2 emissions analysis

China is currently undergoing rapid urbanization. Urban CO_2 emissions have increased tremendously due to increased energy consumption. For example, in the four municipalities in our study, CO_2 emissions were 1258.69 MT in 2008, accounting for 6.5% of the national emission, even though these municipalities covered only 1.2% of China's territory. From 2005 to 2008 CO_2 emissions from the four cities increased rapidly at nearly 3.1% per year. The per capita CO_2 emission for China was 14.77 tons/capita in 2008, while for Beijing, Tianjin, Shanghai, and Chongqing they were 14.89 tons/capita, 23.34 tons/capita, 23.94 tons/capita, and 9.86 tons/capita, respectively. As centers of wealth and creativity, with high population densities and good economies of scale, urban areas must play a leading role by emitting fewer GHG and by tackling global climate change. This issue is a vital concern for both China and the rest of the world.

In a previous work, Dhakal [4] reported on historical changes in energy use and CO_2 emissions in the four mega-cities. In contrast to our study, he used the decomposition method to estimate total CO_2 emissions. Using the same data sources, our results on total CO_2 emissions and per capita CO_2 emissions are closely similar, aside from a few unit errors. However, Dhakal's research focused mainly on energy intensity, which is similar to our carbon intensity in principle, but with a different emphasis. Carbon intensity more directly reflects the impact of the economy on emissions. Our results on the cities using different methods advance the knowledge on urban contributions to CO_2 emissions. Urban energy restructuring and reducing CO_2 emissions are key measures for national emission reduction in the future.

Nowadays, urban-scale energy and emission analyses are weak in China, due to the unavailability of energy data on prefecture-level cities. With increasing urbanization, governments should devote more attention to the urban emissions issue.

4.4. Uncertainty analysis

An emission inventory is always estimated based on available knowledge, available data, emission factors, equipment parameters, models, etc. Thus, uncertain parameters and a lack of basic data would be more likely to result in uncertainties in the emissions estimation [22].

Generally speaking, the statistical margin of error is within $\pm 5\%$. In this paper, the major uncertainties identified in CO_2 emission estimates from the energy consumption of study areas may have resulted from: (1) uncertainty in energy consumption; (2) uncertainty in emission factors; or (3) uncertainty in the oxidation rate.

The energy consumption data used in this study was obtained from the 2009 *China Energy Statistical Yearbook*. However, the annual yearbooks revise previous statistical data. In addition, national statistics are not entirely consistent with regional statistics. Nevertheless, this paper applied the national statistics. There are also uncertainties in the yearbooks' official calculations.

For the CO_2 emission factors, we used default data from the 2009 *China Energy Statistic Yearbook* and the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*. These factors are integrated emission factors for overall China or the entire world. No accurate, specific factors are available for Beijing. Although it was reasonable to use these default factors, there were also many differences concerning the regional environment, technology levels, production status, etc.

As recommended by IPCC, the oxidation rate used in this paper is 1. However, it is well known that all the energy used in the process cannot be totally consumed, as some fuel is insufficiently combusted. Therefore, the actual oxidation rate should be less than 1. As there were no precise methods or proper equipment to measure the oxidation rate, the default value of 1 was used.

Emissions from interstate (e.g., aircraft and trains) and international (e.g., ocean-going ships) transport constituted a further

source of uncertainty. Transport vehicles and vessels also consume amounts of energy, but are not accounted for in local CO_2 emissions [23]. However, this part transport energy used was relatively small, and can reasonably be ignored.

Although these uncertainties cannot be avoided, they can be reduced through improved data availability and methods. At the end of the day, even with the uncertainties, our results fairly represent the overall energy consumption, fuel-related CO_2 emissions, and carbon intensity of the country. Our method is relevant for making macroeconomic calculations for a large region, and the results can be used to verify the accuracy of other models and methods.

5. Implication and recommendations

Using the mass balance method, this paper quantified the temporal relationship among GDP, population, and CO_2 emissions in some representative cities and provinces in China for years 1990, 1995, 2000, and 2005–2008. Our findings provide direct evidence that regional economy intensity, energy use, and population have a significant impact on local CO_2 emissions. The energy itself may be categorized as either low-carbon-emitting or high-carbon-emitting. Although energy efficiency is improving in China, it still cannot meet the world average [7]. China must use more efficient and cleaner energy and coordinate regional energy consumption in order to reduce CO_2 emissions.

China has set itself the ambitious target of decreasing carbon intensity by 40–45% between 2005 and 2020, as announced at Copenhagen. Several strategies have been put forward to achieve this aim.

First and foremost, the energy structure must be restructured and energy efficiency improved. Note that coal accounts for about 70% of China's total energy structure. It is not only the dominant primary energy, but also the dominant source of CO_2 emissions. Hence, improving the energy structure would be an effective way to control CO_2 emissions. On the one hand, industries could reduce their reliance on coal and increase their use of cleaner, renewable energy sources (wind, solar, natural gas, nuclear power, geothermal, biomass energies, etc.) [18,24–26]. On the other hand, efficient production equipment and techniques could be introduced [27] to make substantial reductions in energy use and emissions. In addition, energy could be recycled to improve its efficiency [28].

Second, the economic structure needs to be adjusted. China still lags far behind the developed countries, so it has ample potential to maintain relatively fast economic growth at present. A sustainable low-carbon economy would be the best approach for China. A low-carbon economy refers to an economy that has a minimal output of GHG emissions. China is currently locked into a traditional economic development model, i.e. high input, high consumption, high pollution, and low efficiency. It is vital for China to switch to a low-carbon economy, i.e. high technology, low input, high profit, and low emissions, in order to achieve low-carbon intensity. Care should be taken to promote the development of the information technology industry and high-technology industries, raise the percentage of high-tech industries in the industrial mix, and reduce the percentage of energy-intensive industries [6].

Third, laws, regulations, and institutions are administrative means of controlling CO_2 emissions in China. They provide the basis from which to build strategies to restrain energy use by factories and industries and to guide energy restructuring [8]. The revised *Energy Conservation Law of China* was implemented on April 1, 2008, and the *Renewable Energy Law* entered into force on January 1, 2006. Meanwhile, a new long-term energy initiative is underway.

Finally, and most importantly, the public must be made aware of the importance of saving energy and reducing carbon emissions. Information about energy conservation and low-carbon solutions could be disseminated in various ways.

6. Conclusion

Our analysis of Mainland China's provinces and municipalities revealed a number of interesting findings about energy consumption, CO_2 emissions, carbon intensity, and per capita CO_2 emissions. The results showed that energy consumption, total CO_2 emissions, and per capita CO_2 emissions have increased several-fold across twenty years of a booming economy in China. What is encouraging is that carbon intensity decreased about 22.4% from 2005 to 2008. Although this refers to CO_2 emissions from energy consumption only, emissions from other sources may show the same trend. Moreover, because coal combustion is the major source of CO_2 emissions, energy restructuring is urgently needed. Owing to the large population and the high living standard of a prosperous society, the projected continuous economic growth will lead to more CO_2 emissions if steps are not taken to reduce CO_2 emissions [29]. In the meantime, the increasing use of clean energy will replace energy from coal and oil. As the next step, future research could assess potential CO_2 emission reduction methods. The research on CO_2 emissions should also be expanded to cover all sources, including land use, traffic, waste, etc. Furthermore, the previous research focus on CO_2 should be broadened to include biogeochemical and physical aspects in the search for effective tools to mitigate climate change [30]. Finally, the establishment of GHG emission inventories for urban areas would complement national GHG emission studies.

Acknowledgements

This article was funded by the China Scholarship Council (CSC), China QianRen Program, and Natural Science and Engineering Research Council of Canada (NSERC) Discovery Grant.

Appendices A–C. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.rser.2011.07.005.

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